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GENERAL MOTORS CORPORATION

TECHNICAL REPORT
ON

INVESTIGATION OF PRECURSOR IONIZATION IN FRONT OF THE SHOCK WAVES OF HYPERSONIC PROJECTILES

BY

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[redacted]

SEPTEMBER 1963

FOREWORD

This report is one of a series of related papers covering various aspects of a broad program to investigate the flow-field variables associated with hypersonic-velocity projectiles in free flight under controlled environmental conditions. This research is being conducted in the Flight Physics Range of General Motors Defense Research Laboratories, and is supported by the Advanced Research Projects Agency under Contract No. DA-04-495-ORD-3567 (Z). It is intended that this series of reports, when completed, shall form a background of knowledge of the phenomena involved in the basic study and thus aid in a better understanding of the data obtained in the investigation.

The material in the present report was originally presented as a paper at the AIAA Conference on the Physics of Entry into Planetary Atmospheres, held at the Massachusetts Institute of Technology, Cambridge, Massachusetts, on 28 August 1963.

ABSTRACT

An experimental attempt has been made to measure the precursor electron density as a function of distance ahead of the shock front of hypersonic projectiles in a ballistic range. The electron density just preceding the shock front has been measured as a function of projectile velocity and of ambient pressure. For velocities up to 6,700 m/sec and pressures up to 30 mm Hg the measured density of electrons in the vicinity of the shock front is of the order of 10^9 e/cm^3. The maximum electron density of the precursor ionization increases almost exponentially with velocity. At a fixed pressure, the electron density increases about 30 times for an increase of velocity from 5,300 to 6,700 m/sec (18,000–22,000 ft/sec). The electron density also increases with pressure, but this variation is not so explicit.

An additional experiment has shown that, at least in the considered region of velocities from 5,300 to 6,700m/sec, photo-ionization is the dominant mechanism and electron diffusion plays only a secondary role.

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I. INTRODUCTION

The presence of electrons in front of hypersonic shocks in shock tubes has been observed[1-4]* and theoretically investigated[5, 6] by several investigators. D. L. Jones[7] observed precursor electrons in front of the cylindrical shock waves produced by exploding wires. Finally, S. C. Lin[8] attributed the unexpectedly large radar cross section of Col. John Glenn's MA-6 capsule during his reentry from orbit to the presence of a cloud of precursor electrons in front of the shock front created by the vehicle during its reentry into the atmosphere.

It seems, then, that the presence of free electrons ahead of shock waves is an established phenomenon. However, the mechanism which is responsible for their existence is not completely understood at the present time. Wetzel[6] gives a very elegant treatment of the problem and shows that for electrons diffusing ahead of the shock front large diffusion coefficients are possible; his results are in agreement with Weymann's[1] measurements. On the other hand, Hammerling,[2] Groenig,[4] and Lin[8] seem to favor the theory in which the ultraviolet radiation from the shock front ionizes the gas in front of the shock. Finally, at least as far as shock tubes and exploding wires are concerned, there is the possibility of photoemission of electrons from the walls due to the initial flash as well as due to the shock. The fact that some of the signals travel with the velocity of light also suggests some form of photoemission from the walls. Of course, the precursor ionization observed during the reeentry of the MA-6 capsule could not be attributed to photoemission, and the shock front has to be the only cause of observed electron clouds.

*Raised numbers in parentheses refer to references, given at the end of this report.

In order to resolve these difficulties, and to separate the phenomena associated with the presence of the initial flash and walls from the ionization created by the shock front, it is desirable to study the precursor ionization in front of the shocks of bodies moving at hypersonic velocities under controlled conditions. The measurements made during the actual reentry of hypersonic ballistic vehicles and space vehicles are valuable but expensive, and cannot be easily controlled and interpreted. Some measurements are certainly possible in wind tunnels, but the instrumentation must not obstruct the flow of incoming gas and hence measurements have to be done by indirect techniques. A focused Fabry-Perot microwave interferometer developed by Primich and Hayami[9] seems very suitable for this purpose. Finally, a variety of measurements can be done in free-flight ballistic ranges, where hypersonic models can be flown easily with velocities well in excess of 6,000 m/sec under well controlled environmental and flight conditions.

An attempt has been made at GM Defense Research Laboratories to establish the nature and measure the magnitude of precursor ionization ahead of the shock front of a hypersonic sphere launched in a free-flight ballistic range at different velocities and pressures. The results of this investigation are presented in this report.

II. EXPERIMENTAL ARRANGEMENT

The experiments were performed on the GM DRL free-flight ballistic range, which is schematically depicted in Figure 1. The first part of the range consists of a cylindrical tank 60 cm in diameter and 14.44 meters long. The second part is a cylinder 2.4 meters in diameter and 14.11 meters long. The whole range can be evacuated down to 0.5 μ Hg. In the experiments in the range, a copper-coated plastic sphere with a diameter of 15 mm was placed in a plastic "sabot" container (Figure 2) and accelerated in a launch tube of a light gas gun.[10] After leaving the launch tube the sphere separates from the sabot (Figure 2B) and, when the sabot is stopped at the "sabot catcher" (Figure 1), continues its flight alone.

In order to simulate high-altitude conditions and to keep the water vapor content as low as possible, the range was evacuated down to 0.5 μ Hg and then filled with dry air up to the desired pressure. The pre-flight chamber (see Figure 1) is filled with helium under the same pressure as the gas in the range. The purpose of the helium is to prevent combustion and slow down the hot hydrogen which is used to accelerate the sphere and its sabot in the launch tube. To prevent the mixing of the helium and range gas, a valve (see Figure 1) keeps them separated before the firing; a fraction of a second before the firing is initiated the valve opens to permit the unobstructed flight of the model.

On the end of the range a shielded probe was mounted as depicted in Figure 3. An aluminum plate, shielded by a brass screen to eliminate any static pickup due to the eventual charge-separation in the flow field of the sphere, was biased with a positive potential of 16 volts and then connected to ground through a resistance of 5 kΩ. The purpose of the bias was to establish an electric field

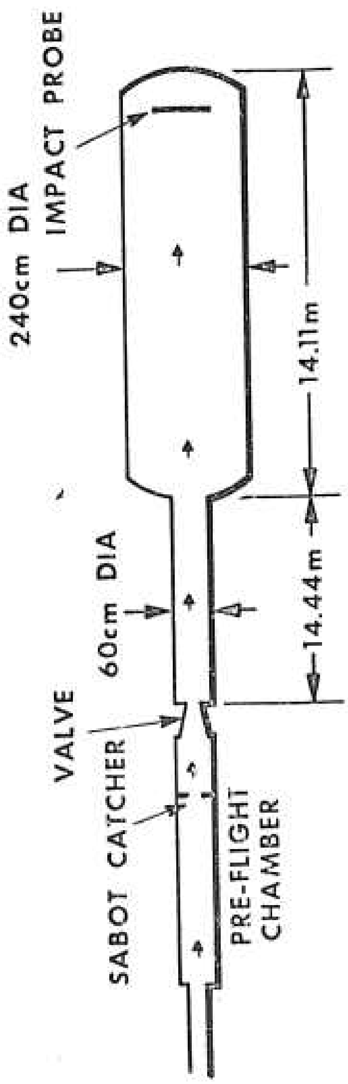

Fig. 1 Free Flight Ballistic Range

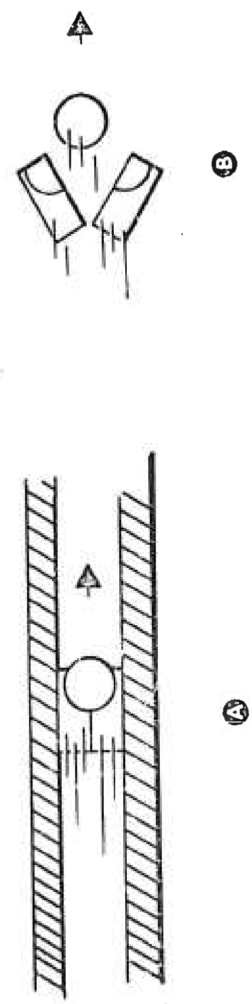

Fig. 2 Launching of the Sphere in a "Sabot" and Sabot Separation

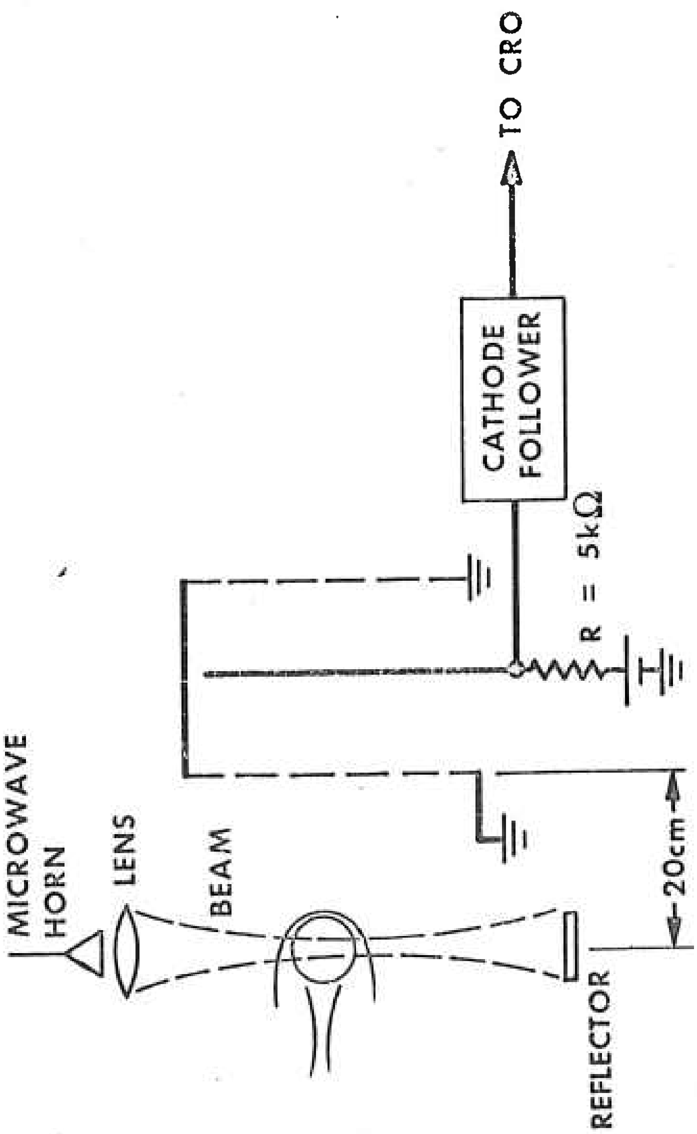

Fig. 3 The Shielded Probe and Microwave Trigger

in the space between the shield screen and the plate, in order to force all electrons which are photoemitted from the plate to return back to the plate and not give any net contribution to the current through resistor R. This field also helps to collect the electrons which are created by photo-ionization within the probe, as well as diffusion electrons which penetrate through the screen ahead of the shock front.

The flow of electrons into the metal plate lowers the plate potential. These changes in the potential are recorded on an oscilloscope, the starting time of the record being approximately the time when the sphere is about 20 cm ahead of the shielded plate. A low-power microwave fan beam parallel to the shielded plate, as depicted in Figure 3, is interrupted by the model and the change in reflected microwave signal is used to trigger the recording oscilloscope.

A typical oscilloscope record is shown in Figure 4. The two traces represent the same phenomena but are taken with different gain in order to extend the dynamic range. The record ends at impact and, for the purpose of numerical interpretation, is replotted in Figure 5, where the abscissa is the distance from the impact and the ordinate is the voltage across the resistor R.

In order to separate the electron diffusion from the photo-ionization, the experiment was modified as depicted in Figure 6. Diffusion electrons cannot penetrate the retarding potential barrier of -16 volts in Region I between the first shield grid A and the metal strips B, and they are deflected and returned back to the grid. Photoemitted electrons from the strips B are also collected by the grid. Electron-ion pairs created in Region I are collected by the grid and the strips, respectively.

In Region II, behind the metal strips and parallel to them, runs a thin conducting wire. The wire cannot be seen looking from the front end of the probe and no photoelectrons can be emitted from the wire due to the light source in front of the probe. Thus, the only possible source of electric charge in Region II is photo-ionization of air within this region. The wire C was connected to a positive

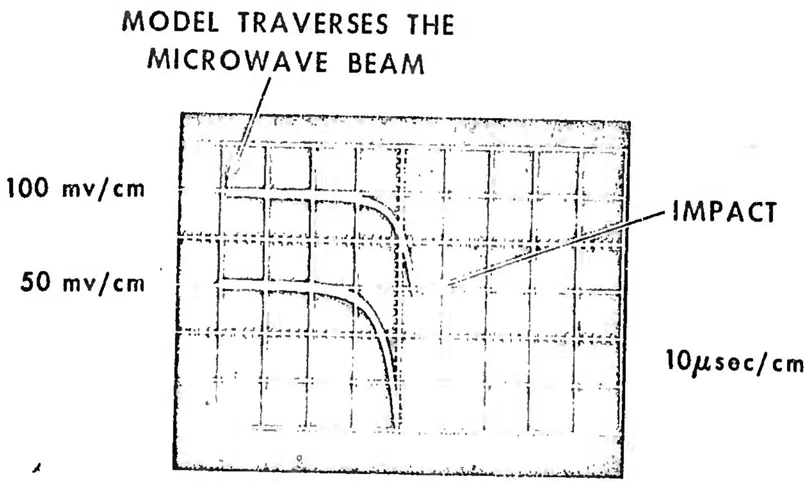

Fig. 4 Typical Oscillogram of the Voltage Across the Resistor R=5k Ω. Upper Trace: 100 mv/cm, 10 μsec/cm; Lower Trace: 50 mv/cm, 10 μsec/cm

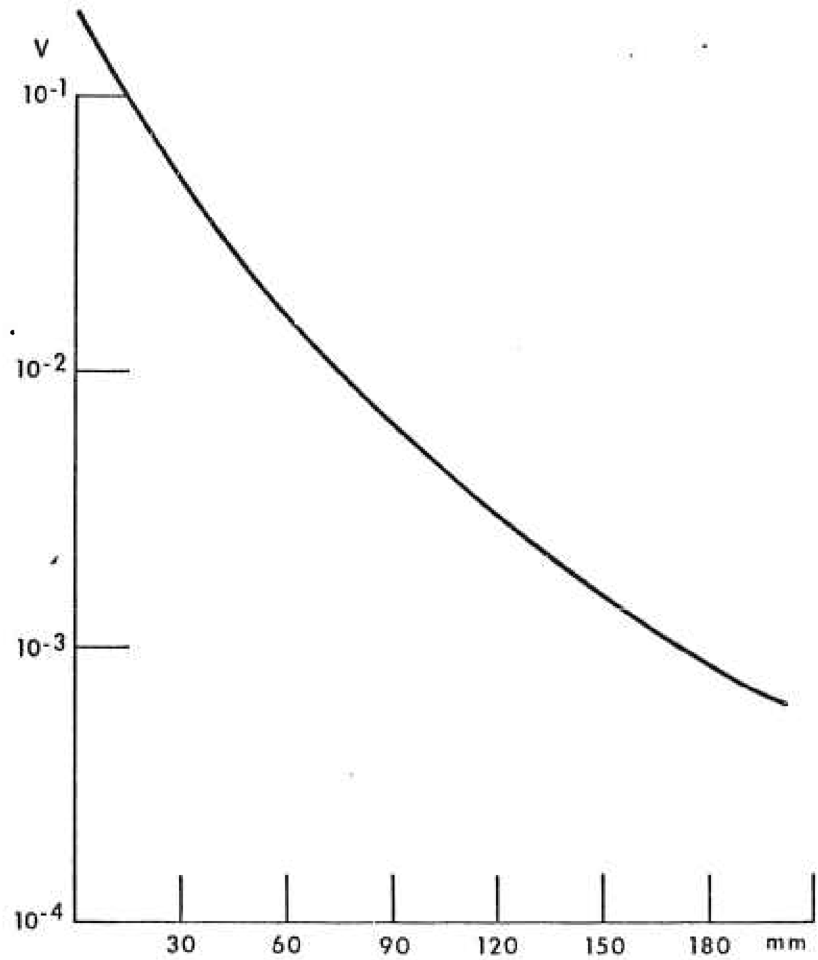

Fig. 5 Voltage Across the Resistor R=5k Ω as the Function of the Distance of the Projectile From the Impact Probe (See Fig. 3). Ambient Pressure 30 mm Hg, Velocity of the Model 5334 m/sec.

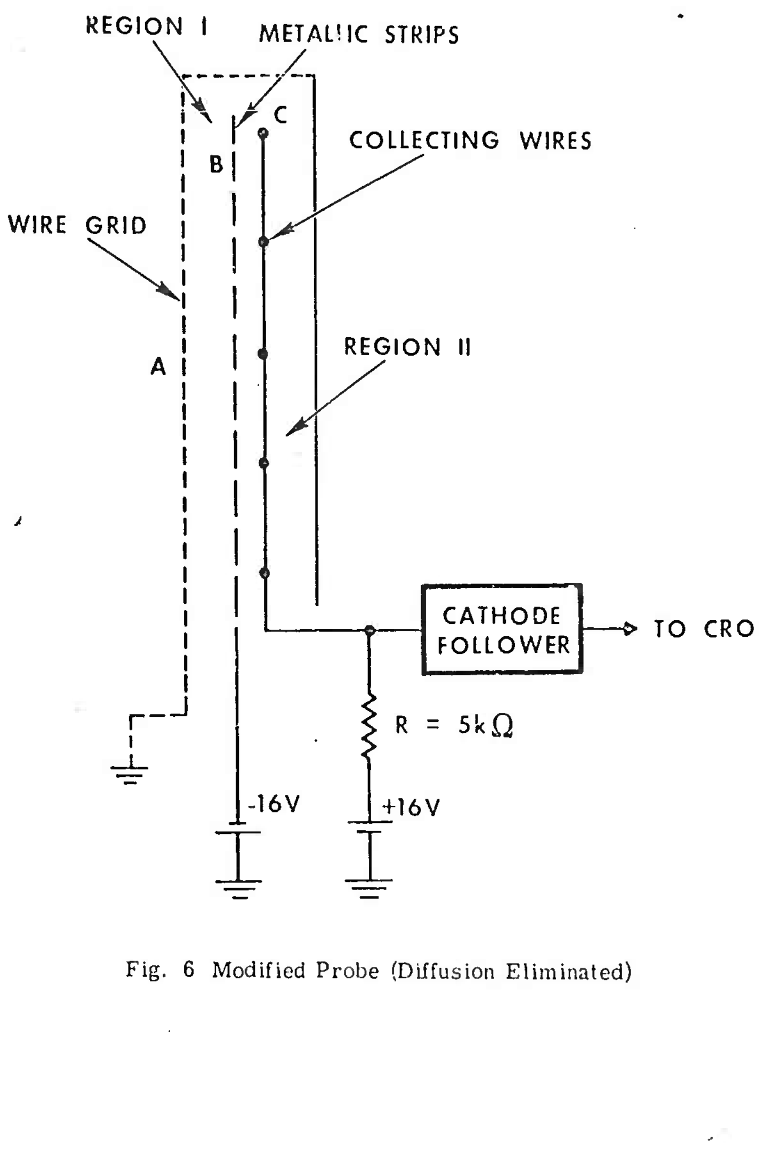

Fig. 6 Modified Probe (Diffusion Eliminated)

potential of +16V through the resistor of 5,000 Ω. The electrons created by photo-ionization in Region II are then collected by the wire C and the change of the potential across the resistor R is recorded on the oscilloscope. Therefore, in the apparatus of Figure 6, reduction in wire voltage should be a direct measure of electric charge created by photo-ionization of air forward of the shock front.

III. RESULTS

From Figure 5, one can deduce that the variation of the signal is an almost exponential function of the distance of the projectile from the impact probe. The discrepancy between an exponential curve and the actual record might be due to the geometry of the probe. Also, recent investigation by Wetzel[13, 14] shows that "lifting" of precursor profiles can be explained by considering the frequency dependence of the absorption cross section of the gases in which the precursor ionization is being observed.

The experiments were conducted for pressures of 1, 3, 10 and 30 mm Hg at velocities in the range from 5, 300 m/sec to 6, 600 m/sec. The peak values of voltages across resistor R are given in Figure 7 as functions of velocity and pressure. The graphs of the voltage across the resistor R as a function of distance from the impact plate normalized with respect to the peak voltage are given in Figures 8, 9, 10 and 11 for various launchings, at the pressures of 1, 3, 10 and 30 mm Hg. Finally, the values of the normalized voltage averaged over various velocities are given for the above pressures in Figure 12.

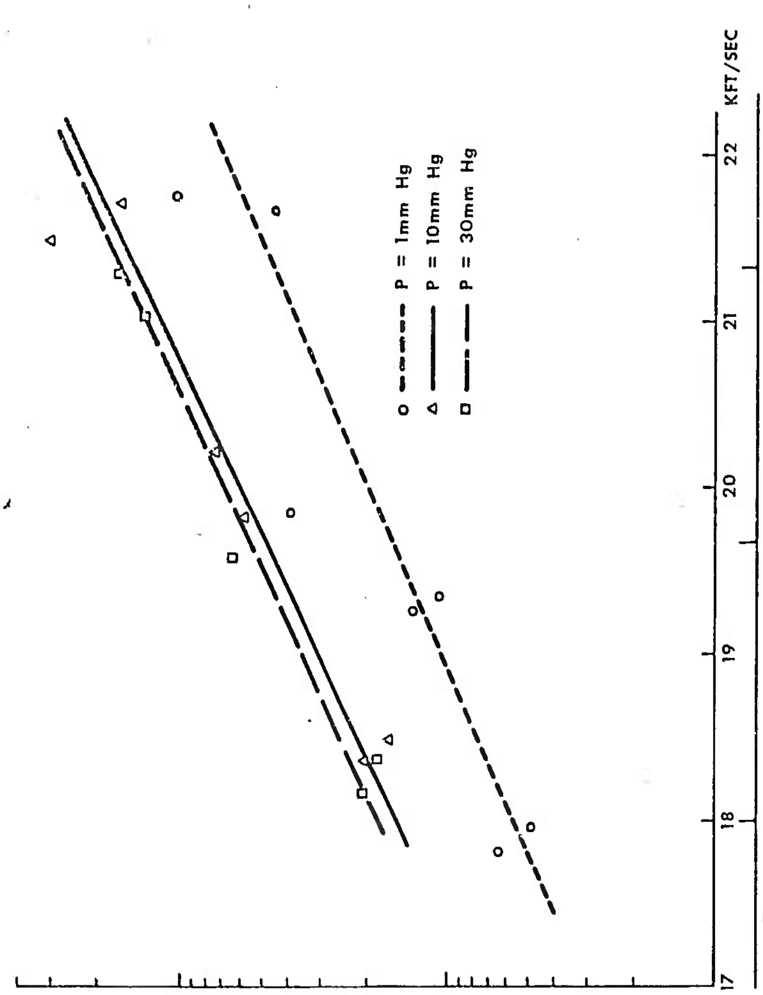

Fig. 7 Maximum Voltage Across the Resistor R=5000 Ω as a Function of Model Velocity and Ambient Pressure

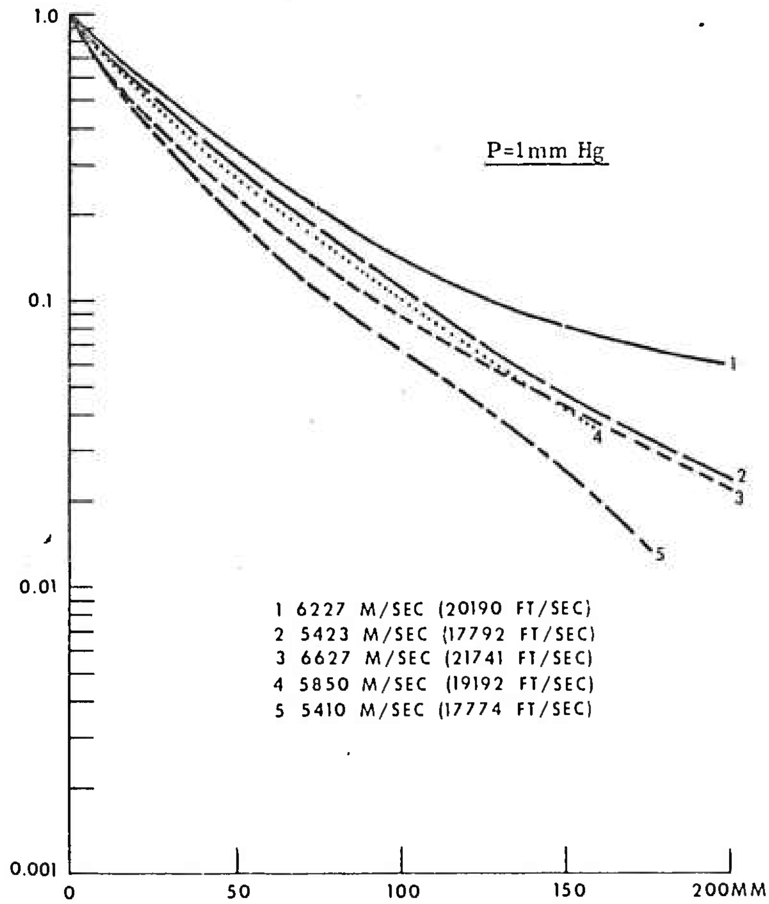

Fig. 8 Voltage Across Resistor R (Fig. 3) Normalized With Respect to its Peak Value as a Function of the Distance of the Projectile From the Impact Probe for the Ambient Pressure of 1 mm.

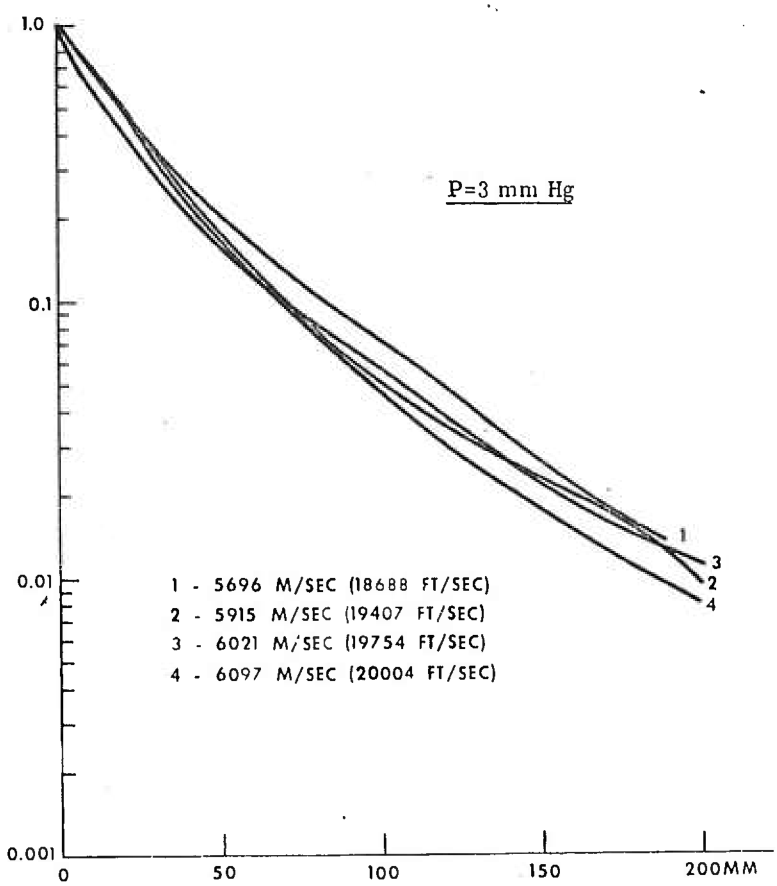

Fig. 9 Voltage Across Resistor R (Fig. 3) Normalized with Respect to its Peak Value as a Function of the Distance of the Projectile From the Impact Probe for the Ambient Pressure of 3 mm Hg

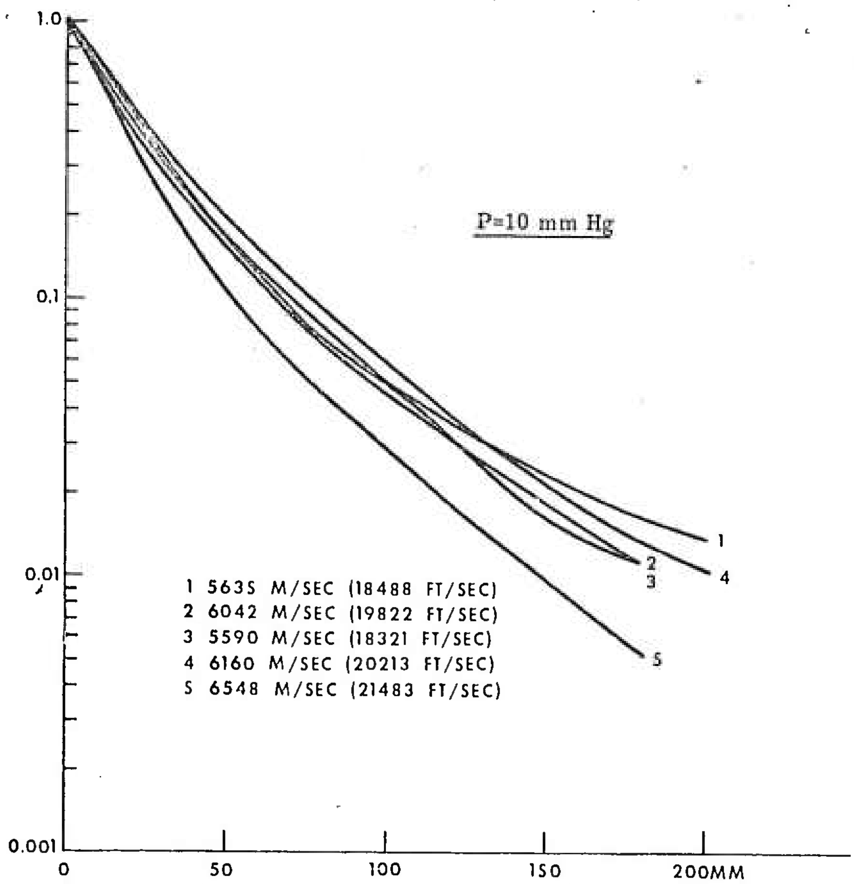

Fig. 10 Voltage Across Resistor R (Fig. 3) Normalized With Respect to its Peak Value as a Function of the Distance of the Projectile From the Impact Probe for the Ambient Pressure of 10 mm Hg

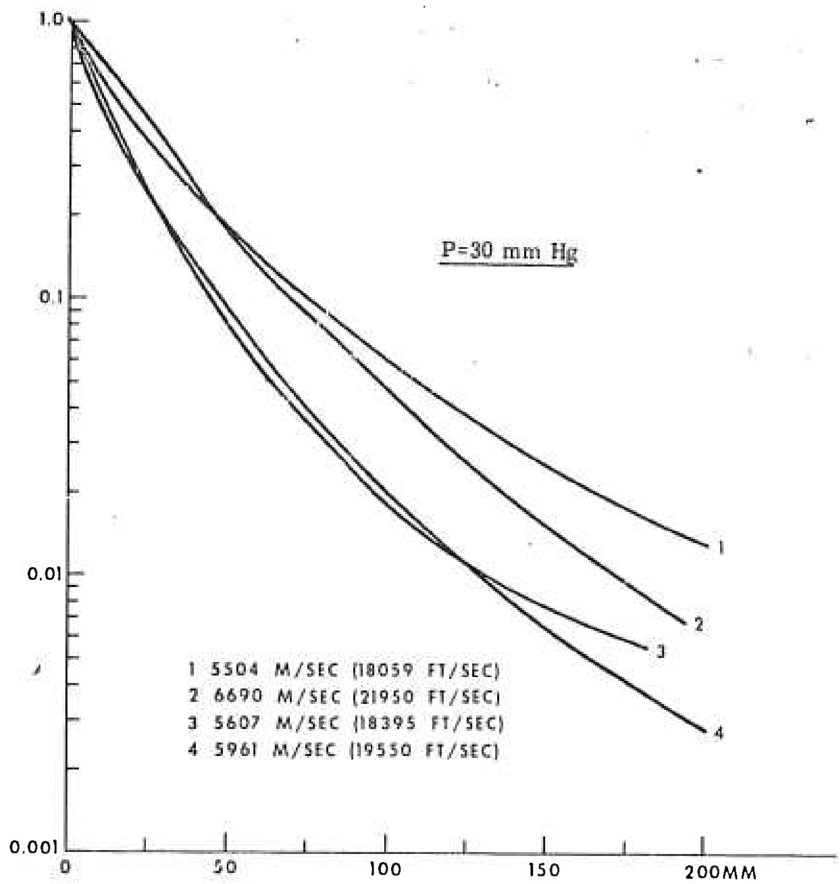

Fig. 11 Voltage Across Resistor R (Fig. 3) Normalized With Respect to its Peak Value as a Function of the Distance of the Projectile From the Impact Probe for the Ambient Pressure of 30 mm Hg

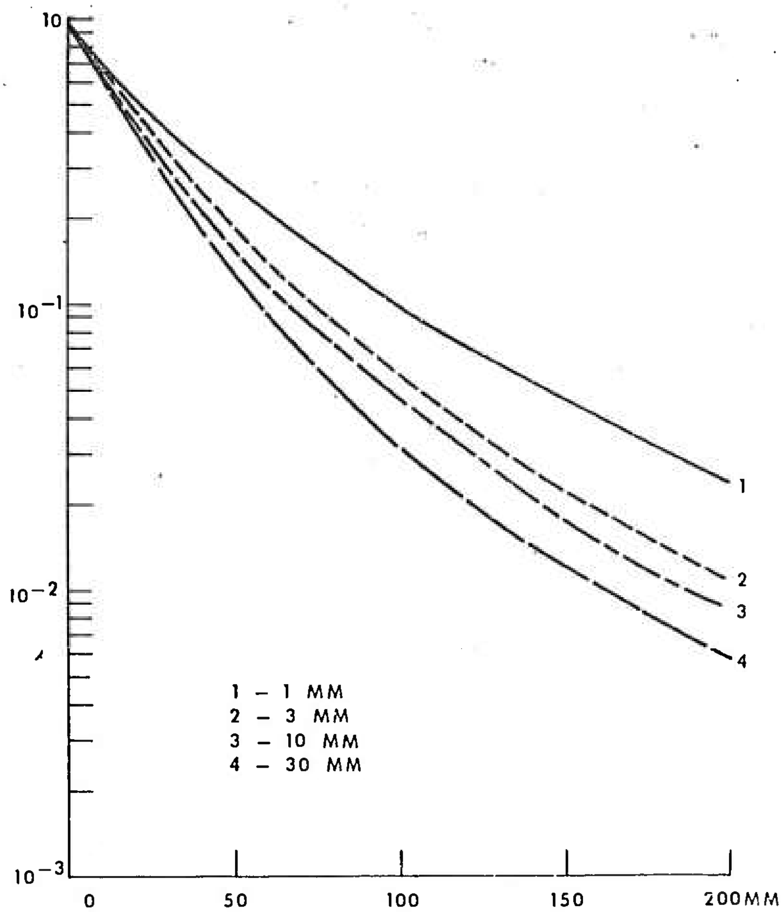

Fig. 12 Average Values of the Normalized Voltage Across Resistor R (Fig. 3) as Functions of Distance of the Projectile From the Impact Probe and Pressure

IV. DISCUSSION OF RESULTS

While it is difficult to give immediately a complete theoretical explanation of the observed precursor ionization, an additional experiment designed to separate diffusion from photo-ionization indicates that the latter is the dominant mechanism responsible for creation of precursor electrons. When the results obtained with the modified probe were corrected for additional distance due to the displacement of the region in which measurements were performed, the corrected peak value of the voltage across the resistor R was in the same region as the peak voltages across resistor R for other measurements. Both electron diffusion and photo-ionization were measured in unmodified experiments, but only photo-ionization in the modified experiments; however, no significant difference in either magnitude of peak voltage or shape of the signal was observed. From this, one is led to believe that electron diffusion is of secondary importance for creation of precursor electrons, at least in the observed range of velocities and pressures.

Another very important fact is that the curves representing the variation of voltage across resistor R have (for fixed pressure) almost the same shape, more or less independent of velocity (Figures 8, 9, 10 and 11). The attenuation rate increases with pressure, as would be expected.

The scattering of results in Figures 7 thru 11 can be attributed to several causes. First, assuming that the photo-ionization of the air is the main cause of precursor ionization, the absorption spectrum of both O_2 and N_2 contains a large number of closely spaced bands between 740 Å and 850 Å for molecular oxygen and around 800 Å for molecular nitrogen.[11] A small change in the radiation spectrum

might change the absorption coefficient appreciably. A more detailed knowledge of the radiation intensity as a function of wavelength and direction is required in order to interpret the results more accurately.

Camm, et al[12] have measured the absolute intensity of radiation in ambient air in a low-density (20μ Hg) shock tube. However, the spectral resolution of their measurements in the region around 1000Å is not sufficient to permit a detailed quantitative interpretation in this case. Also, measurements in a shock tube cannot be used to determine the angular distribution of radiation of the shock front of a hypersonic sphere.

Second, the projectile did not always impact at the center of the probe; however the scattering of impact points was not large. The sides of the square probes were fifteen centimeters long and the impact points were never further than 2.5cm from the center of the probe.

The amount of water vapor was kept below 0.1 percent, except for launchings at the pressure of 1 mm Hg when the percentage of water vapor fluctuated from 0.05% to 0.6%. It is possible that some scattering of results was due to variation in the amount of water vapor.

Finally, although extreme care was taken to make the probes as similar as possible, the fact that each measurement required a new probe might also be partly responsible for some dispersion of the final results.

With a few approximations one can obtain an estimate of the electron density of the precursor ionization. These approximations simplify the actual geometry of the experimental setup and permit determination of the order of magnitude of electron density.

Because the electrons created by the photo-ionization in the probe are swept by the biasing field towards the collecting electrode with a velocity which is several orders of magnitude greater than the velocity of the projectile, the

current through resistor R represents the rate at which the electrons are generated in the observed region in the probe. The current i through the resistor R is

$$i = \frac{V}{R} \tag{1}$$

where V is the observed voltage across the resistor. Expressing this current as the flow of electric charge Q through the resistor (which is equivalent to the rate at which electric charge is created within the probe) one has

$$\frac{dQ}{dt} = \frac{V}{R} \tag{2}$$

or

$$dQ = \frac{1}{R} V dt \tag{3}$$

If one denotes the distance from the impact plate to the projectile by x, then during the time dt the projectile will move the distance dx, i. e.

$$dx = -u dt \tag{4}$$

where u is the velocity of the projectile and can be assumed constant during the short time of observation (approximately 50 μsec). Changing the independent variable in Equation (3) from time t to distance x using the relation of Equation (4), one has

$$dQ = -\frac{1}{uR} V dx \tag{5}$$

The total charge which passes through the resistor R, up to the certain time t when the projectile is at the distance x from the probe, is equal to the total charge which would be accumulated within the probe if there would be no mechanism for charge removal such as the applied biasing electric field. This charge would be created by radiation of the shock front from the moment when the model is launched up to the time when the model is at the distance x from the plate:

$$Q = -\frac{1}{uR} \int_{\infty}^{x} V(x) dx \tag{6}$$

If one assumes exponential variation of voltage with distance (from Figures 8-12), i.e.

$$V = V_0 e^{-\frac{x}{x_0}} \tag{7}$$

where V_0 is the maximum voltage and x_0 is the characteristic "e-folding" distance, then Equation (6) can be integrated to give

$$Q = \frac{1}{uR} x_0 V_0 e^{-\frac{x}{x_0}} \tag{8}$$

The number of electrons N equivalent to the charge Q is

$$N = \frac{Q}{q} = \frac{x_0 V_0}{q u R} e^{-\frac{x}{x_0}} \tag{9}$$

where q is the charge of an electron.

This is the total number of electrons created in the region between the grid and the collecting plate up to the moment when the projectile is at the distance x from the probe. If the grid were not there, this number would be increased by a factor of ξ=1.414 (grid interception coefficient). With this correction the number of electrons becomes

$$N = \frac{\xi x_0 V_0}{q u R} e^{-\frac{x}{x_0}} \tag{10}$$

Neglecting recombination, this is the total number of electrons which would be there if no probe were present. For a characteristic distance of the order of 2.5 cm, velocity approximately equal to 6,000 m/sec and peak voltage equal to one or more volts, N is of the order of 10^{10} electrons.

In order to determine the electron density within the probe one has to know the exact distribution of radiation (and diffusion) in each direction from their source, the hot plasma. Within the scope of present estimates, one can assume that electron density within the probe decays exponentially away from its highest value at the point at which the projectile will eventually hit the probe, i.e. within the probe. Thus,

$$n = n_0 e^{-\frac{\rho}{\rho_0}} \tag{11}$$

where n is electron density averaged over the depth of the probe, n_o is its maximum value, P is radial distance from the point of impact and P_o is a constant (see Figure 13). The total number of electrons within the probe is hence

$$N = 2\pi l \int_{P=0}^{P_1} n\, P\, dP$$
$$\approx 2\pi l\, n_o \int_0^{\infty} e^{-P/P_o}\, P\, dP = 2\pi l\, n_o\, P_o^2 \tag{12}$$

where P_1 is the equivalent limit on P (see Figure 9) and l=1 cm is the depth of the probe. Using N from Equation (10) in Equation (12) yields

$$n_o = \frac{\xi\, x_o\, V_o}{2\pi l\, P_o^2\, q\, u\, R}\, e^{-\frac{x}{x_o}} \tag{13}$$

For small x, P_o can be estimated to be close to x_o, i. e. 2. 5 cm. In order to get an idea of the order of magnitude of n_o, one can normalize x_o and P_o with 2. 5 cm and n with 6, 000 m/sec. Then, substituting the values for ξ, l, q and R, Equation (13) becomes

$$n_o = 0.1819 \cdot 10^9 \left(\frac{x_o}{2.5\,cm}\right)\left(\frac{2.5\,cm}{P_o}\right)^2\left(\frac{6000\,m/sec}{u}\right) V_o\, e^{-x/x_o}\ \frac{e}{cm^3} \tag{14}$$

Thus, the peak electron density should be of the order of 10^9 e/cm^3 for the peak voltage of the order of a few volts.

The actual electron density is certainly not smaller than this estimate. First, the grid interception ratio, which is the ratio of the total grid area divided by the area of the holes, is not a constant but depends on the angle of incoming radiation as a result of the finite size of the wire (see Figure 14). When the projectile is close to the probe, only radiation within an angle of about 60^o will enter the probe.

Further, the angular distribution of radiation probably has a peak in the direction of flight, so the concentration of electrons has a more pronounced maximum at the impact point and decays rapidly (P_o is probably less than 2. 5 cm) away from it. Therefore, the preceding calculations can be regarded as a lower limit on the electron density of precursor radiation.

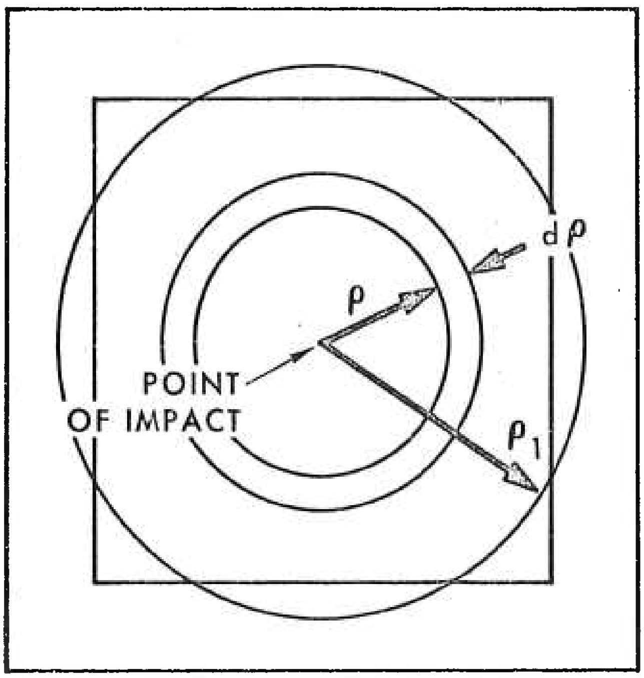

Figure 13 Impact Probe - Front View

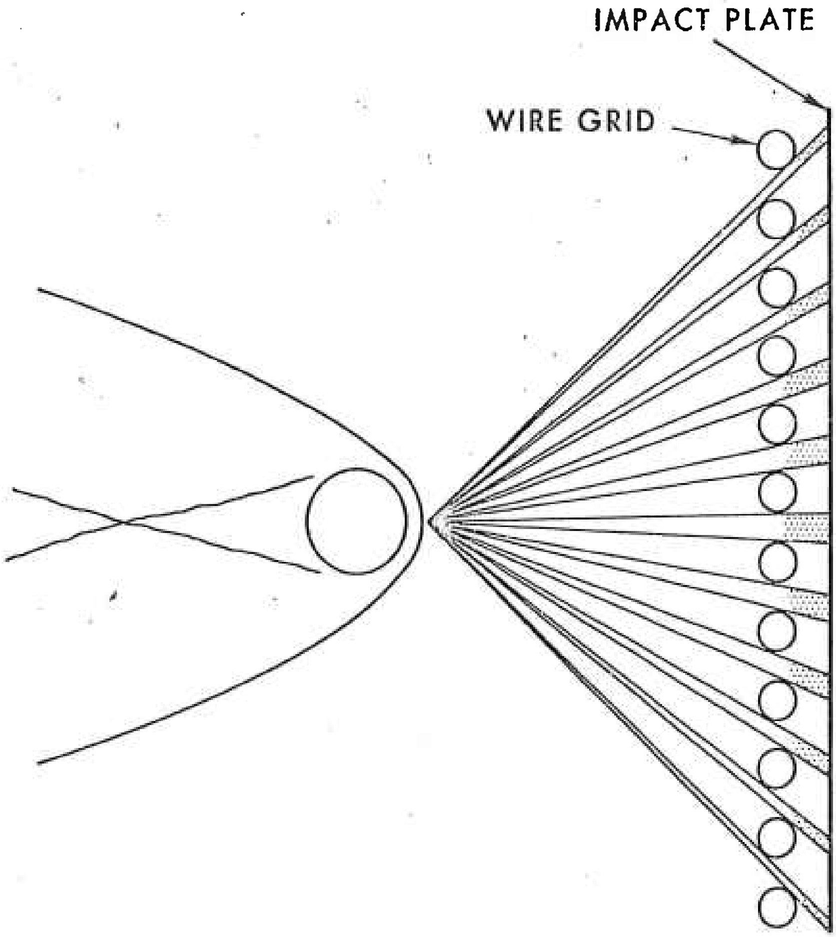

Figure 14 Radiation Shielding Due to Wire Grid
(Not to Scale)

V. CONCLUDING REMARKS

The described experiments have shown the feasibility of measuring ionization levels ahead of the shock front of hypersonic bodies. They also have shown that it is possible to separate the contributions to the total electron density due to diffusion and photo-ionization.

Several approximations were made in order to obtain a quick estimate of electron density. It is believed, however, that the order of magnitude is fairly correct.

The electron density is mainly a consequence of photo-ionization in the observed range of velocities and pressures. However, the possibility of electron diffusion-controlled precursor ionization (in accordance with Weymann's[(1)] measurements) at lower velocities can not be ruled out at the present time.

In addition to ionization, the radiation from the shock front can possibly excite and even partially dissociate gas molecules,[(15)] so that this "preheated" gas would have higher internal energy than is normally assumed in shock-front studies. It would be desirable to obtain, in addition to more precise measurement of electron density, more information about the state of the gas just preceeding the shock front.

Finally, it should be pointed out that the presence of an inhomogenous electron density can have an important influence on the radar cross section of reentry vehicles. It can act as a tapered termination to increase absorption and decrease reflection, consequently decreasing the radar cross section. Or, if the electron density is sufficiently high, it can increase the radar cross section up to an order of magnitude,[(8)] particularly for lower frequencies. It can also be an important factor to take into account when the loss of communications with a reentry vehicle (reentry blackout) is considered.

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GM Defense Research Laboratories, General Motors Corp., Santa Barbara, Calif.

INVESTIGATION OF PRECURSOR IONIZATION IN FRONT OF THE SHOCK WAVES OF HYPERSONIC PROJECTILES, by Srbislav Zivanovic. TR63-217E. September 1963. 31 p. incl. illus., 13 refs.

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3. Microwave Equipment-Applications
4. Plasma Physics

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II TR63-217E
III Zivanovic, Srbislav

(Descriptors) Microwave equipment, plasma physics, gas ionization, hypervelocity projectiles, atmosphere entry, plasma sheath, hypervelocity guns.

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I DA-04-495-ORD-3567(Z)
II TR63-217E
III Zivanovic, Srbislav

(Descriptors) Microwave equipment, plasma physics, gas ionization, hypervelocity projectiles, atmosphere entry, plasma sheath, hypervelocity guns.

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